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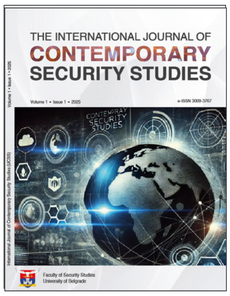


*Research article*

# The Role Of Nanotechnology in Fire Protection

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**ABSTRACT**

Nanotechnology provides new solutions for numerous applications that significantly impact almost every aspect of our society, including medicine, smart cities, the military, agriculture, and industry. Additionally, nanostructures are increasingly applied in fire protection. Application of nanotechnology and nanomaterials, compared to traditional materials, can extend the preservation of material integrity under direct exposure to fire and its effects. This undoubtedly eliminates or reduces the possible consequences of fire, which, in addition to safety benefits, also has significant economic benefits. The present short survey sought to summarize the use of nanotechnology in fire protection, including fireproof materials, the construction industry, nanotextiles, and nanosensors. Finally, there is a brief discussion of the possibilities of using the Internet of Nano Things (IoNT), as well as the potential risks this revolutionary technology, as well as nanotechnology, may pose to humanity.

**KEYWORDS**

Nanotechnology; nanomaterials; fire protection; fire retardant; IoNT; benefits; risks.

## 1. Introduction

Nanotechnology is considered one of the main driving forces of the 21st century and is believed to offer solutions to many of the challenges facing humanity. Nanotechnology is a revolutionary, multidisciplinary scientific discipline that enables the understanding of phenomena and materials at the nanoscale. Structures, devices, and systems composed of nanomaterials exhibit new properties and functions due to their nanoscale dimensions. They can be utilized across all scientific disciplines, such as biology, chemistry, physics, and engineering. This heterogeneous technology is defined by its scale – the prefix "nano" denotes one billionth of a meter (0.000000001) and, accordingly, enables manipulation of substances at the atomic level, in dimensions from 1 to 100 nm (Drexler et al., 1993). The European Commission in its 2022 recommendation, revised the 2011 definition, and states: "Nanomaterial means a natural, incidental, or manufactured materials consisting of solid particles that are present either on their own or as constituent particles in aggregates or agglomerates, and where 50% or more of these particles in the number-based size distribution, fulfil at least one of the following conditions: one or more external dimensions of the particle are in the size range of 1 nm to 100 nm…" (European Commission, 2022: 4-5).

The word "nanometer" was first proposed by Austrian chemist Richard Zsigmondy, Nobel Laureate in Chemistry in 1925, for his work on colloids and the invention of the ultramicroscope. However, the credit for the conceptual foundation of today's nano-world belongs to Nobel Laureate in Physics Richard Feynman. At the annual meeting of the American Physical Society held on December 29, 1959, at the California Institute of Technology, Feynman gave a talk titled "There is Plenty of Room at the Bottom," in which he posed, among other things, the question of why the entire 24 volumes of the Encyclopedia Britannica could not be placed on the head of a pin (Feynman, 1960). In this famous lecture, he explained how scientists could control and manipulate atoms and molecules.

The term nanotechnology was first introduced by Professor Norio Taniguchi of the Tokyo University of Science at an international conference of the Japan Society of Precision Engineering in Tokyo in 1974 (Hulla, 2015; Sadhu, 2006). In his paper titled "On the Basic Concept of Nanotechnology," Taniguchi used the term nanotechnology to describe processes occurring at the nanometer scale, relating to the processing, separation, consolidation, and deformation of materials atom by atom or molecule by molecule (Taniguchi, 1974).

The golden era of nanotechnology began in the 1980s when Harold Kroto, Richard Smalley, and Robert Curl, Nobel Laureates in Chemistry in 1996, together with students James Heath and Sean O'Brien, discovered fullerenes (Kroto et al., 1985). Among the pioneers of the nano-world, Eric Drexler of the Massachusetts Institute of Technology (MIT) holds a prominent place. In 1986, he published the book "Engines of Creation: The Coming Era of Nanotechnology" (Drexler, 1986). Drexler's vision of nanotechnology is often referred to as "molecular nanotechnology." It is based on the "bottom up" concept – producing objects atom by atom, or "top down" – building from the top down.

The definition of nanotechnology was agreed upon in 1998–1999 after consultations with experts from over 20 countries and has achieved a certain degree of international acceptance. After about 60 countries developed nanotechnology activities between 2001 and 2004, it became clear that without this definition and a corresponding long-term vision, nanotechnology would not have developed at the same accelerated, conceptually unifying, and transformative path (Roco, 2011, p. 428). In the same period, many countries around the world established national-level programs, partly inspired or motivated by the National Nanotechnology Initiative, which officially began in January 2001 (Hulla et al., 2015).

Mihail Roco, a leader in nanotechnology, identified four phases in the development of nanotechnology products. The fourth phase, the development of molecular nanosystems (2015-2020), includes intelligent design of molecular and atomic devices, leading to "unprecedented understanding and control over the fundamental building blocks of all natural and man-made things" (Roco et al., 2011; Nayyar et al., 2017). There is no doubt that Roco was right, as control and manipulation of matter at the atomic level play a vital role in shaping scientific priorities.

In addition to extensive research and commercialization of nano-products in almost all branches of science, nanomaterials can play a significant role in fire protection. Present-time nanomaterials, components of various products, underscore the need for an adequate safety response (Soutter, 2022). Nanotechnology and nanomaterials, and their applications, offer new opportunities for developing more efficient materials that can improve fire resistance, ensuring greater safety for those at risk. Further research into nanostructured materials contributes to a better understanding of their thermal, electrical, and chemical properties, enabling improved design of equipment and devices for fire protection. Rabajczyk, Zielecka, and Gniazdowska (2022) believe that nanotechnology in fire protection represents a combination of scientific innovation and practical safety.

## 2. Perspectives and Use of Nanotechnology in Reducing Fire Risk

Fire hazards continue to pose serious threats to human life, the environment, and infrastructure. In recent years, nanomaterials have emerged as a promising frontier in flame retardancy, owing to their superior thermal stability, high surface area, and multifunctional properties. As particles enter the nanometer range, their surface area-to-mass ratio increases, and this is associated with greater reactivity (compared to bulk materials). The impact of using nanomaterials is reflected in shortening response times, the detection and extinguishing of fires, and the reduction of concentrations of toxic, flammable gases and dust, thereby reducing the possibility of combustion products spreading over greater distances and thereby reducing consequences and protecting the environment (Singh et al., 2025).

Nanotechnology is used in materials that reduce fire risk and increase safety, such as construction materials and structures, paints, coatings, fire protection equipment, and devices (e.g., nanosensors) (Temane & Meek, 2024; Mullins-Jaime & Smith, 2022). Nanomaterials incorporated into coatings and protective paints protect materials from fire exposure (Lahtela, Turku & Kärki, 2023), creating a barrier to fire penetration into building materials (Yang et al., 2021). In addition to using fire-resistant paints, fire-resistant glass can be used, which prevents fire spread and enables safe evacuation from the building (Azmy, 2024). The addition of nanoparticles can prevent or slow the spread of flames on materials affected by fire, thereby increasing the time for an adequate response, facilitating evacuation, and facilitating fire extinguishing (Kolya & Kang, 2024). This property is particularly applied in construction and industry, where it contributes to the safety of buildings and equipment in preventive phases.

Rabajczyk *et al.* (2021) state that nanostructures are incorporated in protective clothing and other equipment. The application is reflected in improving the fire resistance of materials and their properties under exposure to flames (Li et al., 2024), elevated temperatures, and combustion products (Qu et al., 2023; Kim, Lee & Yoon, 2021). Nanoparticles, such as metallic oxides (zinc dioxide, titanium oxide) and carbon nanotubes (CNTs), are incorporated into textiles to enhance their flame-retardant properties. Nanotechnology-based fabrics are used to create lighter, more durable, and more effective fireproof clothing for firefighters and other professionals in high-risk environments.

Improving the mechanical characteristics of materials used for personal and protective equipment can enhance material resistance, strength, and flexibility, as well as reduce the amount of material needed to make the equipment. Nanomaterials are also thought to affect the action of water and other firefighting agents, thereby preventing the action of aggressive and dangerous substances that may occur during technological accidents and disasters. Such properties of nanomaterials help make protective and other equipment (footwear, clothing, helmets, goggles, breathing apparatus, protective filters, etc.) used by firefighting and other emergency services (Lin et al., 2024; Zhu, 2025). The increased efficiency of equipment and devices through the introduction of nanotechnology contributes to the efficiency of fire extinguishing (Qu et al., 2023), while the development of lightweight yet durable nanomaterials enables the development of innovative equipment, thereby enabling easier and safer handling by firefighters.

The use of nanomaterials is increasingly prevalent in modern technical protection systems, which are used for fire detection and monitoring, as well as for detecting explosive mixtures, gases, and explosives. Their application is evident in the use of nanodetectors – sensors that monitor changes in defined parameters, indicating early signs of danger. Sensors can be stationary or portable, facilitating widespread and rapid deployment and enabling better monitoring of parameters in working and living environments (Whitehill et al., 2024). This allows precise detection of early fire signs, which, on the one hand, reduces false alarms and, on the other hand, enables detection in its initial stage, making further localization and extinguishing easier.

Concrete, glass, coatings, steel, and wood are the most widely available nano-enabled products in the building construction industry. Silica, $TiO_2$, iron oxide, and carbon nanotubes are common nanomaterials added to concrete to increase density and strength, and, in turn, fire resistance (Jones et al., 2019). Fire-proof glass, using either silica fume or nano-silica, can prevent rapid fire spread, enabling safe building evacuation (Gibb et al., 2018). When applied to paint and drywall, the intumescent layer creates a char. This acts as a fire retardant because char is a poor conductor, offering better fire protection for the material behind it. Nanocoatings may include nano-sized boron nitride or nanoclays, which can be used to fortify building materials and aid in fire resistance (Mullins-Jaime & Smith, 2022). When steel structures are exposed to high temperatures, their strength and rigidity are at risk, and nanomaterials can provide excellent fire resistance, in particular nano-$TiO_2$ (Wang, Han, & Ke, 2006). The flammability of wood products may limit utilisation, with fire safety a significant concern across various applications. To overcome the weaknesses and use wood safely, flame-retardant properties need serious consideration, including the addition of nanoadditives. The use of nanoparticles in wood coatings, such as zinc oxide (ZnO), titanium dioxide (TiO2), silica (SiO2), carbon nanotubes, or graphite, can enhance wood's functionality in terms of durability and fire resistance (Turku, Karki, & Lahtela, 2023). The nanoscale and high surface area of nanomaterials make them more effective at low concentrations than conventional compounds, an enormous advantage industrially and economically. For example, the TiO2-coated wood was found to reduce the flammability of the wood and the spread of flame, compared to the uncoated sample (Jasmani et al., 2020). Furthermore, the ZnO–$TiO_2$ double-nanostructures can absorb large amounts of heat, dilute flammable gas concentrations, and adsorb harmful acid gases during the decomposition process.

In addition to benefits, it is necessary to emphasize the potential risks that nanotechnologies bring to the field of fire protection. The rapid pace of nanotechnology development and commercialization has apparently outpaced the availability of health, environmental, and safety data (Dimitrijevic, 2011). Currently, research on the chronic effects of exposure to nanomaterials is insufficient, and many studies indicate adverse health effects (Savolainen et al., 2010; Olawoyin, 2018). For example, ultra-fine titanium dioxide particles are suspected occupational carcinogens, whereas nano-zinc oxide is linked to inflammation, cell proliferation, and cytotoxicity. Amorphous silica nanoparticles are considered to be relatively low risk; however, there is insufficient evidence to declare nanosilica 'safe', as some evidence of cytotoxicity remains. Adverse health effects of carbon nanotubes are inflammation, respiratory distress, clotting, fibrosis, vascular damage, and other cardiovascular effects. On the other hand, there is a general lack of research on the properties of nanoparticles in relation to their ignition and explosion potential (Dimitrijevic, 2010). However, the increasing use of engineered nanomaterials could give rise to concerns about increased risks to human health and the environment.

## 3. Conclusions and a Look to the Future

Nanotechnology is widely cited as one of the most exciting and important technologies of the twenty-first century. The rapid technological development of engineered nanomaterials is expected to hold enormous potential for new products and applications across several industrial and consumer sectors. In light of the negative impacts that fires can cause, the development of new technologies, such as nanotechnology, promises greater possibilities than ever before, to protect human lives and property. This includes the development of new equipment, construction materials, nanotextiles, monitoring suspended particles and carbon monoxide using nanosensors, firefighter protection, and, of course, economic benefits.

Nanomaterials are widely regarded as having great potential, but they may also pose new classes of problems for human health and the environment. It is not easy to anticipate with certainty what will happen when nanomaterials are released to the general public or into the environment at large. Regulation of nanomaterials has been a highly controversial issue in recent years, as has the capacity of international governance to meet the complex regulatory demands posed by nanomaterials. Therefore, responsible governments should adopt a precautionary approach and be more involved in global regulatory cooperation.

In addition to nanomaterials, the development of the Internet of Things (IoT) is seen as a new concept gaining enormous popularity in modern wireless telecommunications. IoT, rather than merely merging computers and people, is evolving into the unification of smart objects or things in the real world using Information and communications technology (Ashton, 2009; Gubbi et al., 2013; Bresciani et al., 2018). The combination of nanotechnology and IoT has created the Internet of Nano Things (IoNT). The main building blocks of IoNT are nanotechnologies, namely nano-devices ranging from 1 to 100 nm (Akhtar & Perwej, 2020). IoNT uses the most sophisticated and advanced methodologies for data collection, enabling IoNT to expand its base from the existing to a broader circle of new and advanced applications compared to the Internet of Things. This opens up an entirely new dimension of IoNT use, enabling interaction and communication with home appliances, pollutant-monitoring sensors, and surveillance sensors. Moreover, IoNT can provide much more detailed, cheaper, and up-to-date images of cities, homes, and factories. A large amount of information can be collected in real time using numerous nanosensors to improve the quality of life, health, and infrastructure (Jarmakiewicz & Parobczak, 2016). These miniature sensors, interconnected via nanonetworks, can pave the way for new research in fire protection. IoNT, although in its initial stage of research and development, has the capacity to provide highly sensitive sensors for the detection of changes in the concentration of dangerous gases and smoke. Furthermore, it is expected that far more sophisticated fire detection could enable better-coordinated responses from all emergency services. Nevertheless, the potential use of IoNT technology may give rise to issues due to a lack of regulation, thus posing significant security and privacy concerns.

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